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THE PROBLEMS OF HUMID TROPICS - AN OPPORTUNITY FOR REASSESSMENT OF HYDROLOGICAL METHODOLOGY

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ABSTRACT

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RÉSUMÉ

The Problems of Humid Tropics -- An Opportunity for Reassessment of Hydrological Methodology.

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A Historical Perspective

Hydrology, as everybody knows, is the science concerning itself with the dynamics of the hydrological cycle, i.e. with the circulation of water on this planet. Not everybody realizes, however, that this dictionary definition is more a statement of a program than a statement of fact. Hydrology has never been practiced in this global water context and it is only very recently that such an approach has been even contemplated as feasible and, indeed, necessary. Inspite of this realization, it is by no means clear hov such a program can be executed, hov much integration is desirable and necessary among the historically formed autonomous sciences of oceanography, climatology, meteorology and atmospheric physics, glaciology, hydrogeology, and the hydrology of the land surface, i.e. hydrology in the narrow sense.

The recent activity in this area has been stimulated by societal pressures reflecting the emergence of global environmental problems which

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refuse to remain contained within the historical boundaries of the various geo- and bio-physical disciplines. What we must realize in searching for new approaches, is that the present state of scientific methodologies, disciplinary groupings, etc., is not something apriori given or designed to satisfy some platonically ideal classification of the sciences, but merely a result of pragmatic rationalizations of very specific societal pressures of the past era. The development of scientific methodology is a continuing, through not necessarily continuous, process generated by an inherent dichotomy between tools shaped by the past and their inadequacy for tackling many problems of the future.

While we recognize this methodological handicap in connection with hydrology in the broad, or global, context, we are usually less ready to acknowledge it in connection with hydrology in the narrow sense - the land surface hydrology in which we consider ourselves to be expects, which we practice, teach, on which we write learned volumes, guides, textbooks. About this science we tend to project an image of methodological clarity, generality and power capable of "solving" almost any hydrological problem one can think of, as a cursory inspection of any hydrological textbook will testify.

In my opinion, such an image is largely an illusion, or better, a delusion. In fact, I consider the methodological fuzziness and lack of perspective to be much greater in the classical, land-surface hydrology, than it is in the general, or global, hydrology. The problems facing the humid

tropics provide an excellent background against which the deficiencies of contemporary hydrology can be clearly seen.

Historically, the sum total of the present hydrological methodology is the result of about 200 years of efforts to solve various water-management problems in the temperate zones of Europe and North America. Significantly, the bulk of the problems that stimulated the development of hydrology arose only after a continental-scale change in the ecology had been in an advanced stage. Europe was already stripped of much of its original forests, vast areas of land were under intensive cultivation and exotic plants like potatoes and maize were already part of the "natural" conditions. The situation was similar in North America where not only conversion of native forests into farmland was in rapid progress but also the transformation of the prairie into arable land. It was water resources under these already substantially changed conditions that had become the object of intensive development, conditions that became to be regarded as stationary.

Thus the beginnings of hydrology as a science were largely divorced from ecology and the societal pressure on its development came almost exclusively from the desire to utilize local water resources for the rapidly expanding economy, i.e. from the immediate demands of the industrial revolution. It was the building of canals for water transport, water supply for the growing towns, water energy for the growing industry, protection of settlements and agricultural land against floods, and increase of productivity of agricultural

land through drainage and irrigation that stimulated the initiation of measurements of precipitation and streamflow and the development of methods for the estimation of the quantity of water available for these technological purposes.

It is also important to realize that the need for estimating the quantity of water available in streams and wells arose only with the increase of the scale of the related technological projects, i.e. only after this quantity had become a problem. Under the conditions of small-scale development, when the availability of water could be taken for granted (as is still the case with the availability of air), the emphasis was on methods helping to make use of it, e.g. for its extraction from the ground, diversion on water wheels and into canals, distribution within towns, etc. The sciences that were stimulated during this "small-scale era" were primarily hydraulics and fluid mechanics on the one hand structural and mechanical engineering on the other. It is from these roots that the present hydrology has developed as a result of an increase of the scale of the water-related technological projects. And since the theoretical basis of all these disciplines was mechanics, the development of hydrological methodology has followed what can be called a mechanistic tradition. Hydrological problems were initially faced by hydraulic and structural engineers and they naturally approached them with their "tool-kits" containing mostly concepts of mechanics. Thus the movement of water across the land surface was approached via the extension of the mechanics of open channel flow to the mechanics of flow over a flat inclined

plane, the role of the vegetation cover being reduced to the problem of hydraulic roughness. The movement of water through vegetation was reduced essentially to the problem of capilarity, the plants being regarded as passive wicks. The soil has been conceptualized as a "porous medium" whereby the groundwater hydrology has been reduced into the fluid mechanics of porous media.

Where this fluid-mechanistic reductionism (with gravity and friction as the only acting forces) proved to be inadequate, pure empiricism has been adopted which has later been formalized and "intellectually upgraded" into the systems approach. This last addition to the standard hydrological methodology, while heralded as an advance, is in fact a sell-out, an admission of defeat, a step down from trying to explain a process from its underlying causes to merely describing it, fitting the appearance with an ad hoc mathematical structure. By this process, hydrology degenerates from a science into a technique.

Such is, in a nut shell, the methodological heritage of the contemporary hydrology. It is a heritage from the water-resource engineer solving small-scale water-management problems of an industrial society living in a benign temperate climate and an altered ecology which is believed to represent stationary "natural" conditions. In general, such a situation does not encourage the search for a better understanding. Rather, because of the stationarity assumption it favours description of empirical facts. Since the

substance, while not well understood, is believed to be stable over time, all that seems to be needed is to describe the past and use the description as a model of the future.

Paradigm Shift

There is one over-riding difference between the social climate under which the bulk of contemporary hydrological methodology developed and the social climate of the present day.

In the former case it was a climate of man's self confidence, an unshaken belief in technological progress, in the desirability of changing nature by bringing it under man's control, a myopic naivete not seeing beyond the immediate benefit of any given action. In a way it was the culmination of the judeo-christian world-view according to which God made man the master of nature whose sole purpose was to serve him and satisfy his material needs.

As a parenthetic but none the less hydrologically relevant observation, I may note the paradoxical fact that so far the last heir of this judeo-christian religious concept of man's position "above" nature was Stalin with his vision of building a paradise by "changing nature" by means of his grandiose "Great Constructions of Communism" -- ironically, mostly water management projects like huge dams, canals and irrigation systems. For me this is not merely a historical curiosity but a painful personal memory of a

"voluntary" participation on two such "Constructions" in the early 1950's, digging in the mud, listening to fiery speeches about the "victory of man over nature" (sic) and marching to the tu of a song " We will order the rain when to fall and command the wind where to blow...".

The situation today is substantially different. There has been a fundamental "paradigm shift" spreading across political boundaries, transcending religious doctrines, affecting developed as well as developing countries. The romantic optimism and belief in man's mastery over nature has been replaced by apprehension, a growing realization that the sum total of all the local "victories over nature" may add up to a global defeat. The increasing affluence of the industrial nations and the struggle to provide even the basic needs for the rapidly growing population of the developing world conspire to produce an unsustainable stress on the world resources, environment and eventually on the existing social and political structures.

These new concerns are perhaps most clearly apparent in the humid tropics, a geographical region which carries more than its share of the pressure of both the population explosion and the worldwide hunger for natural resources. This disproportionally high intensity of environmental stress manifests itself most visibly by the mass deforestation and the consequent land-use change. While similar to the process that took place in the temperate regions of Europe and North America in the past, its present importance in the humid tropics is higher by an order of magnitude because of

the following reasons. Firstly, unlike our forefathers, we now better appreciate the important role of forests, in particular the tropical forests, in the global environment. Secondly, the rate of the present deforestation in the tropics is much faster than it was in the temperate regions in the past. This aspect, combined with the plausible assumption that deforestation in the tropics may have a deeper impact on global environment than deforestation in the temperate regions, hints at a distinct possibility that rather drastic global changes may now result within a relatively very short period of time. And thirdly, given the rapidly growing population and its higher expectations compared to those of a century or more ago, much more is now at stake if the steadily diminishing resources should be mismanaged.

It is against this background that the hydrological problems of the humid tropics must be seen and the adequacy of the available hydrological knowledge and methodology assessed.

A General Methodological Framework

There are three major aspects which the methodology aiming at advancing hydrological science in the direction most useful to the contemporary needs of the humid tropics must emphasize and which are largely absent from the classical hydrology. They are (1) nonstationarity, (2) macrohydrological processes and (3) bio- or ecohydrology.

All these aspects are gaining importance in hydrology in general, but in the humid tropics their need is particularly urgent. Nonstationarity because of the more than average population growth and the consequently much faster rate of environmental change than in other regions. Macrohydrological processes and ecohydrology because of the unique ecological importance of the region as a global source of atmospheric moisture and oxygen, and a sink of carbon dioxide.

The implications for hydrological methodology are enormous. On the one hand, the necessity to consider substantial changes in hydrological conditions renders ineffective all the standard methods interpreting historical records in the stationary context. On the other hand, the necessity to consider the dynamics of large-scale hydrological processes and the key role of vegetation in the tropical water cycle leaves the hydrologist both emptyhanded and unprepared to develop the necessary tools -- macrohydrological and ecohydrological methodologies are in an embryonic stage and hydrologists are still not getting an education and training necessary to master these new areas. Last but not least, macrohydrological analyses will not be feasible without a qualitatively different data base than the one provided by the classical networks of sparse point measurements hinging on local accessibility and availability of qualified personnel. The new data base will have to comprise "hydrological fields", i.e. time series of areal distributions of various hydrological and related variables. Such a data base is only now coming within reach through the newest remote sensing and data transmission technology.

Because of their importance, the three major new concepts deserve to be discussed in more detail.

Macrohydrology

In the humid tropics, the overall control of hydrological processes by the global atmospheric and ocean circulation is more direct than in other regions because of the unique role of the equator. The vanishing of the Coriolis force on the equator makes the latter behave as a quasi-rigid boundary vis-a-vis both the atmospheric and ocean circulation and gives rise to a special class of motions in the vicinity of the equator. This feature, together with the maximum of the solar radiation input, makes the tropics the prime mover of the atmospheric and ocean dynamics and the location of the maximum water and energy fluxes. The dynamic features originating in the tropics operate on large spatial scales and on a wide spectrum of time scales which vary from diurnal (e.g., convective rainstorms), to weekly (e.g., hurricane generation), to seasonal (e.g., monsoons), to annual (e.g., the southern oscillation).

This stresses the need for analyzing the hydrological conditions and their changes in a broad atmosphere-ocean-land context and forces an explicit accommodation of the fact that the key to understanding hydrological phenomena often lies outside hydrology, certainly outside the domain of the classical hydrology taken in the narrow sense of the word. The major methodological

consequence is a need for the development of dynamic models capturing the essential features of the atmosphere-ocean-land interactions. This is a formidable task which has been approached, though with an uneven emphasis, from all the three corners, with the atmospheric general circulation models (GCMs) being by far the most advanced. While the need for their coupling with the ocean dynamics has been always recognized, the experience with their use in recent years has clearly shown that a more detailed representation of the land-surface process, i.e. of the land-surface hydrology in the first place, is equally important. Because of the reasons given above, the importance of land-surface hydrology in the GCMs is accentuated in the humid tropics.

Presently, there are three major obstacles to an effective coupling of the GCMs and hydrological models, all of them more pronounced in the humid tropics than elsewhere. The first is the methodological difficulty of bridging the "scale-gap" between the GCMs which work on spatial grids of the order of hundreds kilometres and the classical hydrological models which use river basins as spatial units and often treat the scale problem only indirectly through various empirical features like "travel times", different shapes of basin unit responses, etc. In the humid tropics, this problem is exacerbated by the fact that most hydrological models operationally available have been developed for temperate conditions and their structure does not make them readily transferable. The second obstacle, also of a methodological nature, is the fact that, in the dynamical context, the classical hydrological model is at best a "hydraulic machine"; it tends to reduce, as far as

possible, all hydrological processes on the land surface to hydraulic mechanism and whatever is beyond this possibility, is relegated to empirical, or "systems", description. This "mechanistic bias" is a greater handicap for application in the humid tropics where the nonmechanical forcing (e.g. thermodynamics, biochemistry) exerts dominant control over the water fluxes. The third obstacle is a lack of an appropriate data base which, again, is much more acute in the tropics when in the temperate zones.

It is, however, encouraging to note that important steps to overcoming these problems have been taken during the past decade or so, notably in the form of international research projects. Among the most recent and relevant ones in the present context are the Global Energy and Water Cycle Experiment (GEWEX) and the even more ambitious and general International Geosphere-Biosphere Programme (IGBP), also known as the Global Change Programme. As a contribution to the scientific objectives of GEWEX and IGBP in the tropics, the French scientific community has just proposed a new international program called the Tropical System Energy Budget (BEST, standing for Bilan Energétique du Système Tropical).

Nonstationarity

It cannot be emphasized often enough that the over-riding reason for the need to develop dynamical models in general, and for the humid tropics in particular, is the condition of nonstationarity which, though long recognized

to be important on time scales of thousands of years and beyond, has, until very recently, not been regarded as practically important on "human" time scales of decades and centuries. Only the recent explosive expansion of human race and of the not-long-ago unimaginable magnitude of the effects of the byproducts of its civilization, has brought the reality of nonstationarity right into our backyard, so to speak. It is forcing us drastically to change our ways of thinking, not only politically and economically, but scientifically as well -- especially in the areas of environmental and earth sciences whose objects of study are the first potential victims of the collective aggressiveness of human race vis-a-vis nature. As already mentioned, the shrinkage of the time scale on which nonstationarity is becoming significant is presently largest in the humid tropics where the changes induced by "modern" causes (CO_2 concentrations, long-range transport of pollutants) are happening at the same time as the drastic land-use changes which in most of the temperate zone have been spread over several centuries.

This is a historically unique occurrence which has caught us ill-prepared in many areas, hydrology among those on the top of the list -- we are facing here a situation for which we have neither a precedent nor a clear conceptual framework to guide us in its absence. We only have an uneasy "gut feeling" that something can go wrong, perhaps irreversibly, and see only some of the most obvious candidates that are in need of an increased attention. However, recent experiences teach us that great dangers may well loom behind seemingly benign appearances or be otherwise out of our present range of sight.

The awareness of the importance of nonstationarity on relatively short time scales is eroding the very foundations of contemporary methodology of the so called "applied hydrology", in particular its reliance on long historic records and on the modelling philosophy based on the concept of "curve fitting" and "calibration". This topic will be discussed later in a separate section. In the present context, suffice it to say that nonstationarity is giving hydrology a potent impetus to climb one rung higher on the ladder of scientific methodology: from description of observations to their causal explanation, i.e. from empirical to dynamic modelling of physical phenomenon.

Ecohydrology

Given the importance of vegetation in the hydrology of humid tropics and the rate and volume of their deforestation, a deep scientific understanding of the quantitative relationships within the soil-vegetation-atmosphere segment of the hydrological cycle is indispensable for sound hydrological analysis and for any kind of medium-to-long term hydrological assessments and predictions. It is needed for an adequate parameterization of the land-surface processes in the GCMs in order for making it possible to model the present dynamics of the water and energy fluxes in the humid tropics, in particular to find out how much of their rainfall is generated locally, what is the spatial pattern of the prevailing water fluxes over the tropical rainforest, how the interactions between the internal dynamics of the humid tropics and the external forcing influence the basic patterns of the boundaries between the humid and subhumid

tropics and their variatiability. It is obvious that to address these types of questions is beyond the reach of the contemporary mechanics-and-systems-dominated hydrological methodology. Thus quantitative ecohydrology is the key to tackling the three more general problems of immediate interest, namely (a) the local hydrological effects of the local environmental changes, (b) the external hydrological effects of the local environmental changes and (c) the local effects of external environmental changes such as global warming, long-range transport of chemical pollutants and aerosols, etc.

Specific hydrological issues

Apart from the general issues discussed in the preceding section, some methodological differences arise from the different aspects of hydrological processes in the humid tropics as compared to those in the temperate climate. In a nut shell, these aspects are all subsumed in the label "humid tropics" but they must be described explicitly in order to make the methodological consequences stand out clearly.

The most conspicuous feature of the humid tropics is of course the overabundance of moisture ("humid") and solar energy ("tropics") which produce the exuberant vegetation. Its overall dominance of the hydrological processes was mentioned in the preceding section but it is important to point out some aspects of its function which are accentuated in the humid tropics.

One of them is the fact that the evapotranspiration is there seldom constrained by a limited availability of water and proceeds at a "potential" rate which, under these conditions, is then controlled only by the available energy and plant physiology. This seldom happens in the temperate zone where the reduction of the actual evapotranspiration due to a limited water supply causes the potential rate to rise and creates a gradient which figures prominently in all temperate-zone hydrological models, though in many cases it is used improperly. Thus the problem of evapotranspiration in the humid tropics environment focuses the attention to the energy and plant regimes much more than it does in temperate zones.

A related problem arises from the much more prominent role of interception in the humid tropics due to the much higher frequency (often almost regular daily occurrence) of rainfall. The ratio of the moisture flux from the plants into the atmosphere through evaporation and transpiration is thus substantially different than in temperate regions and may necessitate a different parameterization of the evapotranspiration process, in microhydrological studies, in GCMs and in macrohydrological models.

A third problem involves the present relationship among evapotranspiration, local generation of rainfall and photosynthesis - a relationship that is bound to change due to deforestation, the increasing atmospheric concentration of CO_2 and its potential climatic effects like temperature increase, changes in cloudiness, etc. Since photosynthesis

"counteracts" evapotranspiration by preventing water from escaping into the atmosphere and its rate itself is controlled in part by water availability (its summary chemical equation is $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$), the possible changes may be substantial and their direction and broader effects are by no means clear.

Another feature of vegetation which in the humid tropics is much more important than in the temperate zone is its role as a mechanical dissipator of the kinetic energy of rainfall and thus as an efficient buffer protecting the soil from erosion. The importance of this function can best be appreciated when we realize that rainfall intensities and volumes in the humid tropics are by an order of magnitude higher than in the temperate zone. To put it more graphically, many areas in the humid tropics are exposed many times every year to what in the temperate zone would be regarded as 100 to 1000 year rainstorms, i.e. to conditions which would render the affected locality a "disaster area". In quantitative terms, a daily precipitation total in a humid tropics location can be larger than an annual total in a temperate location. The common daily totals in humid tropics are in the vicinity of 200 mm and short-term (5 to 30 min) intensities around 200 mm/hr.

It may well be that this rainfall buffer function is the most important role of the tropical forests for ensuring a continuous long-term habitability of the region. It is not only the order-of-magnitude greater erosive power of the rainfall but also the much higher fragility of tropical soils that

exacerbates the danger of their rapid degradation after their exposition. This fragility is caused by the rapid breakdown of organic matter producing high CO_2 concentrations in the percolating water thus leading to a highly effective weathering. The superimposed continuity of infiltration caused by the overabundant rainfall then leads to intensive leaching of chemicals and leaves behind structurally unstable and generally "poor" soils. Quantitative understanding of these processes is still inadequate but enough is known qualitatively to pinpoint this problem as one of the central areas in which new methodologies are needed and extensive research has to be done.

Another aspect that calls for a revision of the classical hydrological methodology when tackling the problems of the humid tropics is the fact that organic matter assumes there some of the functions that the soil performs in the temperate zone, in particular that it participates more directly in the cycling of nutrients and the storage of moisture.

Even from this short and sadly incomplete list it should be abundantly evident that the problem of the humid tropics is not merely the greater quantities of moisture and energy that, hypothetically, could be entered into the existing theoretical constructs and models as larger input values thus producing correspondingly larger outputs. It can be seen that the increased quantities of moisture and energy by themselves activate processes that are dormant under lower values of these two inputs and for the analysis of which therefore no methodological framework has been developed. Most importantly,

it is evident that these newly activated processes which rise to prominence in these conditions are processes of thermodynamical, chemical and biological nature. This contrasts sharply with the fact that the bulk of the classical methodology developed in response to hydrological problems encountered in the temperate zone is designed for the handling of processes rooted in fluid mechanics.

It may be noted that an analogous change, but in the opposite direction, takes place when the object of hydrological investigation moves from the temperate zone to the arctic or the alpine zones. There the overall decrease of energy inputs drastically reduces the intensity of chemical and biological processes, substantially slows down the fluid mechanical ones and activates those of solid mechanics, like snow drifting, avalanches, ice flow and creep in glaciers etc.

Applications of Hydrology to Water Management

It has already been mentioned that a major component of the present day hydrological methodology grew out of the hydraulic and water resources engineering endeavours in the temperate zone during the past about 200 years. In reality, hydrology has not yet fully separated from these parent disciplines and a lot of confusion exists in regard to their respective aims and methodologies. Not even the professional community has yet fully grasped the basic difference between hydrology - an earth science and water resource

engineering (or more generally, water resource management) - a technology. As a result, hydrology is often charged with solving tasks of technological nature while technological advancements are taken for hydrological discoveries. For example, a recent Canadian occupational brochure for the promotion of hydrology as a profession list almost exclusively water management tasks such as water power generation, irrigation, water quality improvement, etc. as the "hydrologist's challenges". Conversely, many engineering design and operational techniques, such as stochastic generation of synthetic streamflow series for storage reservoir design or transfer-function flow forecasting models have been regarded as advances in the science of hydrology. To make this confusion look more respectable, the term "applied hydrology" has been coined under which such activities as mentioned above are conveniently grouped which is then regarded as "bridging the gap between theory and practice".

For the most part, hydrological concepts that are used in various water resource management applications are either empirical relationships between hydrological variables such as, for example, rainfall and runoff which are formalized through statistical or systems techniques (the Unit Hydrograph concept is a good example), or concepts which allow a hydrological process to be reduced to some fluid-mechanical process which then is solved with the aid of the available physical theory (e.g. flood wave propagation along river channel).

With this background information, it is relatively easy to make an assessment of the standard hydrologic methodologies as to their applicability to water management problems of the humid tropics.

The least satisfactory situation is faced by the planners of long-term development of water resources. If such planning is to have any credibility it must be based on solid estimates of regional water resources and their future variability. The available methodologies are sorely inadequate for this task since they are all based on the assumption of stationarity of the hydrological regime over a period of at least 100 years centred on the present. That is to say, they make an assessment of the water resources from the historic hydrological observations over the past 50 years or so and assume that the situation over the planning horizon (never longer than about 50 years) will not be markedly different. This methodology is coming increasingly under attack everywhere because of the potential of global changes within the nearest few decades. In the humid tropics it has the handicap of probably the fastest rate of these future changes.

Into this virtually unusable category belong the standard methodologies for estimating the long-term mean precipitation, streamflow, groundwater levels and the associated variabilities, the estimation of the frequencies of extreme events and based on them design parameters of various water-related structures such as dams, levees, floodways, water supply systems etc.

A similar and perhaps even more difficult task face the agricultural planners who have to cope, besides the uncertainty in future hydrological regime, with the uncertain future of the soils. This makes the planning of future food production a guess game.

The only hope for limiting the range of these uncertainties is a rapid progress in the monitoring and theoretical understanding of the dynamics of the macroscale processes and the soil-vegetation-atmosphere segment of the hydrologic cycle discussed earlier and a reduction of the rate of the changes currently taking place globally and locally.

The situation is generally better with the applicability of the methodologies concerned with analysis of currently existing hydrological relationships. Based mostly on empirical observations described in systems or statistical frameworks, these methodologies postulate no understanding of the dynamics of the underlying processes and are readily applicable wherever the necessary observations can be made. Unfortunately, such relationships can be of help only for immediate operational applications such as flood forecasting and estimation of design parameters for local structures serving instantaneous needs. However, they have no scientific value and have to be continuously revised (recalibrated) as the natural situation changes since all of them are predicated on stationarity which may be a reasonable assumption only for a very limited time span.

The best prospect have the methodologies for problems that can reasonably be reduced to the simpler problems of applied fluid mechanics, i.e. open channel flow, bank seepage, well yield, etc. While their empirical components such as the hydraulic roughness, hydraulic conductivity, and the like may be subject to changes, their theoretical basis, involving only simple mechanical processes, has a general validity. Moreover, a humid environment may sometimes be conducive to such a reduction. For example, it is well known that most of the present-generation conceptual hydrological models perform better under humid than under arid conditions. This is most likely due to the fact that the basin is most of the time saturated so that the antecedent moisture conditions of individual storms remain more-or-less constant thus eliminating one variable important for the nature of the basin response. However, such advantage may be offset by the likely consequence of shorter lag times between precipitation and runoff and hence less time for effective flood forecasting, evacuation and other hazard-mitigating actions.

In closing this section, an important point should be made which is equally valid for humid tropics as elsewhere. Many sound water management decisions can be made with surprisingly little hydrological information since the lack of knowledge can often be compensated for by a corresponding increase in the robustness and resilience in the design of the relevant facilities and in maintaining flexibility of future options. The contemporary fix on the necessity of the highest level of scientific information for every decision is a comparatively recent phenomenon brought about by the development of the

systems theory in general and the concept of economic optimization (usually understood as maximization of short-term economic gains) in particular. The truth is that in all but the simplest technological decisions the concept of optimization is a fiction because its underlying assumptions, including social, political, economic and other conditions, are changing rapidly and usually unpredictably. It is safe to say that most water-management projects, however thoroughly their design may have been optimized, were far from optimal by the time they were but into operation. The return to conservative decisions with high safety margins and ample flexibility is particularly called for in the environmental context and in regions such as the humid tropics which are undergoing rapid change.

Consequences for hydrological education

The contemporary system of hydrological education is the result of the development of hydrology over the past 200 years as a service discipline to various branches of water-related technologies in the temperate zones of Europe and North America. These technologies include transport, agriculture, forest management, water power development, flood protection, industrial and domestic water supply, urban drainage, to name just the most important ones. As a consequence, the main aim of hydrological education has not been to prepare experts capable of advancing the hydrological science but the strengthening of these various water-related technologies with which this education has been affiliated. Its minor segment provided within the

framework of physical geography has been, until very recently, almost purely descriptive and paid little attention to the dynamics of the processes involved.

Because of these historical reasons, the present system of hydrological education is saddled wi a technological fix. This makes it difficult for hydrologists to address the fundamental problems of hydrology which are not of a technological nature but belong squarely within the domain of earth sciences. The main problem of the present-day hydrological education is that it does not produce scientists but technologists with prime motivation in applying hydrology to other ends. This has led to what has euphemistically been called "many perspectives of hydrology" but means little more than a motley of ad-hoc empirical and often mutually inconsistent methods and techniques whose main connection with hydrology is their use of numbers labelled with hydrological names.

This situation was more-or-less tolerable as long as the human interference with the environment in general and with the hydrological cycle in particular was of a small scale and did not appreciably alter the quasi-stationary conditions established in Europe and North America after the conversion of a substantial part of their forests, prairies and other ecological entities into agricultural land. Under these conditions, there was little incentive to discover the deeper relationships in the hydrological cycle and the educational system responded accordingly - it concentrated on

producing specialists knowledgeable of the ways how to make use of water for the dependent technologies, and neglected to educate specialists focused on water as such. Hydrology is now in a similar situation as would be, for example, geology if it could be studied only via, say, geological engineering; or botany if it had to be studied only as a part of agronomy; or mathematics if it were offerred only as a service discipline to actuarial studies or home economics.

The conditions in the contemporary humid tropics where the idyll of environmental stationarity is about to explode exposes the fallacy of the technologically biased hydrological education better than anything else. Suddenly, there is a need for professionals who could assess the future water resources of this vast region under changed environmental conditions and they are nowhere to be found while the "unit hydrographs" and "flood frequency analyses" offered by the run-of-the-mill experts are of no use. The main responsibility for rectifying this situation (which will become more acute when the global changes start more intensively to affect other climatic zones) lies with the universities which should, without delay, establish streams within earth sciences that would provide appropriate background for specialists in the water-related geo-and bio-physical problems. This development should be vigorously encouraged by international as well as national environmental and water-resource agencies and organizations. For it is these bodies that soon will become the main targets of societal pressures inspired by large-scale changes in water-resource availability which is crucial for sustainable habitability of every region.

Conclusions

The geographical zone of humid tropics with its overabundant supply of solar energy and humidity, and the consequent exuberant vegetation poses unique hydrological problems which the present methodology, developed in response to different natural and social conditions, cannot effectively tackle. The gulf between what is available and what is needed is widened by the fact that the available methodology is predicated on the existence of stationary environmental conditions while those in the humid tropics are highly nonstationary because of the population explosion in the region and the rapid change of land-use resulting from the conversion of rain forests into agricultural land.

Three aspects have been emphasized as deserving major attention in the development of an adequate scientific basis capable of addressing hydrological and water-resource problems of the region, in particular (1) a consideration of nonstationarity in the major geo- and bio-physical processes, (2) the development of a dynamically sound macrohydrology and (3) the development of quantitative ecohydrology. These aspects stand in a sharp contrast to the contemporary hydrological methodology which, because of the underlying assumption of stationarity, favours empirical approaches based on historical observations and which, because of its roots in hydraulic engineering, is heavily biased towards fluid-mechanistic concepts and tends not to do justice to other physical processes.

Finally, it has been pointed out that this situation has serious implications for hydrological education. In particular, it has been recommended that universities should establish streams in the earth science curricula that would provide adequate background in the sciences most relevant to the dynamics of the hydrological cycle. This would make it possible for the science of hydrology to be studied at a similar level as other geo-physical and bio-physical sciences, rather than only a service discipline to various technological programs such as water- resource engineering, forestry, etc. as is the general practice today.